BIOMIMO Design & Test: motion capture and AR techniques to design and test an orthosis prototype

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Abstract — **"BIOMIMO Design & Test" is a software application to aid the process of designing and testing IADs (Intelligent Assist Devices), also known as orthoses. This software combines Augmented Reality (AR), Virtual Reality (VR) and video-based optical motion capture techniques in order to evaluate a prototype without actually constructing it, and to avoid the risk of testing it on a real person. In this paper, as an initial step, it is applied to a 2 DoF (degrees of freedom) arm orthosis.**

Keywords — **Augmented Reality, IAD, Optical Motion Capture, Orthosis, Virtual Prototype, Virtual Reality.**

I. INTRODUCTION

AN exoskeleton or "human amplifier" is a mechatronic system worn by a person which offers the user the possibility of enhancing their physical skills. The term IAD (Intelligent Assist Device) is used for a special kind of human amplifier, a biomechatronic device the purpose of which is to help the user perform a daily activity which requires a certain amount of effort. The word orthosis can be used in the same context. Ikerlan has designed and constructed an upper limb IAD of 5 DoF [1], an exoskeleton designed to help the user perform a routine activity requiring effort in the workplace.

As a preliminary step, and above all to research the issue of the interaction of such devices with the environment, a 2 DoF arm orthosis was designed. This orthosis was not physically constructed, but a virtual prototype was created for testing the performance of the different control algorithms implemented.

The process of analysing, designing and constructing a prototype to detect its defects is an expensive process and it can also be dangerous to test on the real user, especially in the early stages of the investigation, when the aim is just to test different control algorithms.

The use of virtual prototypes, as opposed to creating real ones, whilst not eliminating the need to manufacture an ultimate prototype for the final tests, eliminates intermediate tests with real prototypes which could potentially be dangerous for a user. Virtual prototyping is a widely-researched subject and the main concern in it is the validity of these virtual prototypes in the development of an ergonomic study. In order to undertake these ergonomic studies *JACK* [2] is one of the most used tools. *JACK* is a simulation environment in which virtual humans are placed to perform tasks on virtual prototypes. Reference [3] proposes the introduction of these kinds of studies into the design phase in order to avoid the cost of real prototypes. With the improvement of Virtual Reality (VR) and Immersive Visualisation techniques, largely due to improvements and the falling prices of graphics hardware, one more step has been taken in this area, in an attempt to make the use of the virtual prototype more realistic for the user. Reference [4] shows the comparison of different tools, including *JACK*, and uses immersive visualisation environments in the prototype evaluation. At this stage, the movements are no longer created by the virtual human, but are copied from the real user, using a motion capture system. This new data input enables the movements of the virtual human to be more realistic, but it does not take away the fact that the whole study is being developed into a virtual world.

Motion capture can be considered as the computer's sense of sight, through which it is able to observe the movements of the user. Although this is a fairly new technology, a large number of approaches have been carried out in order to develop the capture process, using various technologies: acoustic, electro-magnetic, mechanical... Currently the most commonly used are optical capture systems for three main reasons: accuracy, speed, and freedom of movement for the user. Within this group we can differentiate between two sub-types: infrared (IR) and video-based capture systems. IR capture systems are more accurate but require rather expensive special hardware (IR cameras). Video-based are those which more closely resemble the sense of human sight, where based on the image, an attempt is made to capture the position and movements of the object or user being observed.

Motion capture techniques are not only used as a data source for the movement of a virtual human, they are also

used in evaluating real prototypes. This technique is widely used in the automotive industry [5], and research has also been carried out on its validity. Reference [6] shows the validity of an IR optical capture system, for the analysis of the posture of the shoulder and the elbow in various tasks. The conclusion of this study, comparing the results obtained by 28 expert ergonomists and those from the automatic system using motion capture, is that the results of the automatic system are similar to the conclusions of the experts, in the 4 tasks considered.

Having thus demonstrated the validity of motion capture systems for the development of ergonomic evaluations on certain tasks, and the vast amount of work about virtual prototyping, in our research we have tried to create an environment to evaluate the correct performance of the virtual prototype of the orthosis, but on a real user. This is possible by applying a new interaction paradigm: Augmented Reality (AR) [7]. The difference between VR and AR lies in the way they treat the real world [8]. VR immerses the user into a virtual world which completely replaces the real world, whilst with AR the user interacts with a mixture of the real world and virtual information.

The study discussed in this paper considers how to use a video-based optical capture and mark recognition system [9], to evaluate the performance of a virtual prototype, generating the movement set-point values based on the real user, and testing the environment-interaction algorithms using a virtual wall by means of dynamic simulation in real time, eliminating the cost and physical risk of using a real prototype.

II. DESCRIPTION OF THE ORTHOSIS

A. Orthosis description

In order to make an initial approach towards the final objective, the IAD or orthosis of 5 DoF [1], and essentially to research the position/force algorithms, it was decided to simplify the system by reducing it to 2 DoF. An orthosis was therefore designed with three main parts: the two which will move jointly with the arm and forearm and a third fixed to the body. In order to achieve the 2 DoF of the moveable parts, two rotating joints were used: one for the shoulder and another for the elbow. As a result, the movement of the arm is limited to a vertical plane. The third main component is a kind of backpack which will be secured to the user's back, as shown in Figure 1, and will withstand all the efforts made by the orthosis.

The main function of the exoskeleton, in so far as it has been designed as a support device, lies in amplifying the torque with respect to the elbow joint exercised by the human muscles when handling loads. In order to guarantee this functionality, the device consists of two DC motors for the two joints. Following a meticulous study of the options existing in the market, it was decided to opt for graphite brush motors from Maxon. More specifically, the *RE 36 ∅36* model, which is capable of supplying power of up to 70 W when operating axially. Each drive is fitted with a planetary gearhead and a tachogenerator also from Maxon,
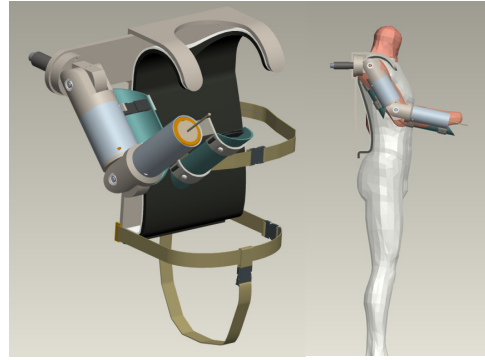

Fig. 1. Virtual prototype of the 2 DoF orthosis.

GP 32C ∅32 1-6 Nm gearhead with 190:1 reduction, and *DC Tacho*, ∅22 mm and 0.52 V tachogenerator. A servoamplifier *Maxon ADS 50/5* is used for current and speed control.

The abovementioned drives are placed near the rotating axes, hidden inside the cylindrical pieces as shown in Figure 1. The forearm part of the orthosis weighs 1.94 kg, and its moment of inertia with respect to the rotating axis is 261 kg·cm^2. The arm part weighs 3.5 kg and has a moment of inertia with respect to the rotating axis of 820 kg·cm^2.

Given that this first orthosis design was created to research the interaction of these devices with the environment, a force sensor was fitted to the designed orthosis at the end of the forearm cylinder, at the level of the user's hand. This sensor was designed by Ikerlan for robotic manipulators and supplies the force exerted at the tip in the 3 spatial coordinates.

Although the design described has not been physically constructed, it has been created virtually. In other words, a virtual prototype has been developed consisting of the dynamic model of the exoskeleton and upper human limb, and of the controller which deals with the positioning of the hand in the workplace and the force exerted by the orthosis against the environment in the event of collision. To this end, a vertical wall at a distance from the user can be activated. The model of the complete system was created at *Simulink*, with the dynamic part imported from *Dymola/Modelica*. The code was obtained by means of *RTW* of The MathWorks and loaded onto an *xPCTarget* compatible PC/104 platform. The simulation is carried out in real time, with an integration step of 1 ms, and being communicated with the motion capture and visualisation system.

B. Position/Force control algorithms

The basic control of an orthosis type device is based on position control, where the user creates the motion set-point value and closes the loop with the help of the sensors possessed by the human body. A key element is the detection of the "intention" of the user and creating the motion set-point value from him. This characteristic, of great interest to researchers, is a fundamental difference between the orthoses and robotic manipulators. Another very important factor to consider is the interaction with the environment, especially from the point of view of controlling the force exerted in order not to harm people
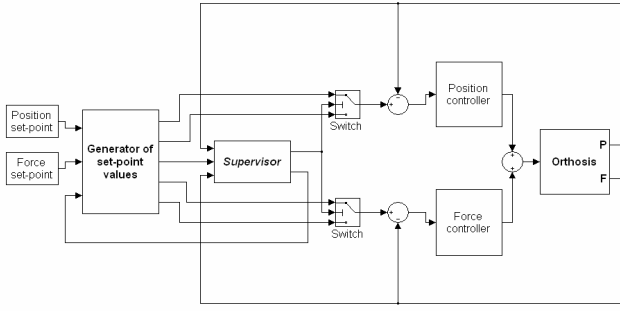
Fig. 2. Structure of the hybrid position/force controller.

Fig. 3. Structure of the impedance controller.

who may be present in the field of action of the robotic device. In robotic manipulators there are two classic types of position/force control: hybrid control and impedance (or admittance) control. It has been considered that these types are valid in the case of an arm orthosis, although they have particular characteristics which differentiate them from the case of robotic manipulators.

A hybrid position/force controller has been used in the orthosis, following the system shown in Figure 2. It basically consists of two independent controls, one for position and one for force, and a supervisor, which depending on the contact with the environment, switches between one type of control and the other. The supervision is based on the information supplied by a force sensor in the orthosis, in this case at the end of the arm. In a more general case, a force sensor system distributed throughout the body/casing of the orthosis must be considered. The supervisor, in addition to the set-point value generator, is responsible for making the transition between controllers "smoothly", to avoid bouncing and to ensure the stability of the system. This system controls with great precision the position of the orthosis and the force exerted on the environment.

Another classic position/force control type, very interesting in the case of orthoses, is impedance control. Impedance control does not need a supervisor and is capable of taking control of a compound task, with phases of free and restricted motion, maintaining the stability of the system without changing the control algorithm. It is based on the idea of controlling the dynamic relationship between the force and position variables of the physical systems. It assumes that in every manipulation task the environment contains inertia and kinematic restrictions, i.e., systems that accept forces as input and respond through displacements (admittances). In turn, the manipulator in contact with the environment must adopt the behaviour of an impedance, responding with a certain force to the displacement of the environment. The general strategy can be established in terms of controlling a motion variable and, in turn, equipping the manipulator with a response to disturbances in the form of impedance. In this way, the interaction between the manipulator and its environment can be modulated, regulated and controlled by acting on the impedance values.

In impedance control, the functional form of the torque of the actuators of a manipulator is well known:
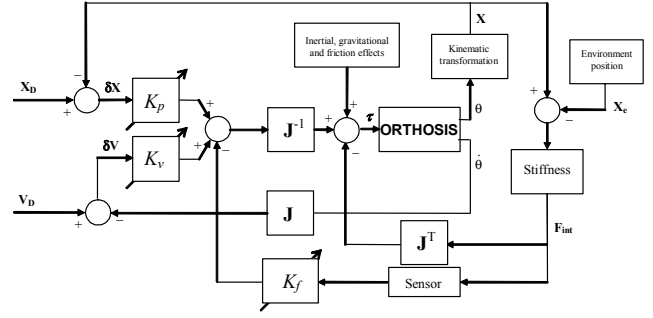
$$\tau_{act} = I(\boldsymbol{\theta})\mathbf{J}^{-1}(\boldsymbol{\theta})M^{-1}K\big[\mathbf{X_0} - L(\boldsymbol{\theta})\big] + S(\boldsymbol{\theta})$$
$$+ I(\boldsymbol{\theta})\mathbf{J}^{-1}(\boldsymbol{\theta})M^{-1}B\big[\mathbf{V_0} - \mathrm{J}^{-1}(\boldsymbol{\theta})\boldsymbol{\omega}\big] + V(\boldsymbol{\omega})$$
$$+ I(\boldsymbol{\theta})\mathbf{J}^{-1}(\boldsymbol{\theta})M^{-1}\mathbf{F}_{int} - \mathbf{J}^{t}(\boldsymbol{\theta})\mathbf{F}_{int}$$
$$+ I(\boldsymbol{\theta})\mathbf{J}^{-1}(\boldsymbol{\theta})G(\boldsymbol{\theta},\boldsymbol{\omega}) + C(\boldsymbol{\theta},\boldsymbol{\omega})$$

(1)

where each line of the second member represents a contribution to the total torque of a different nature: the first line corresponds to terms dependent on the position, the second to terms of speed, the third to terms of force and the fourth to terms of inertial coupling. This equation expresses, in the space of the actuators, the behaviour that the controller must be capable of inducing in the manipulator, in the form of non-linear impedance. The input variables are the desired Cartesian positions and speeds, as well as the terms, linear or non-linear, which specify the required dynamic behaviour, characterised by the magnitudes M, B and K. Figure 3 shows the typical structure of impedance control, where the feedback gains of the position, speed and force loops, K_p, K_v and K_f respectively, depend on the inertia and reference mass tensors, on the stiffness K and on the damping B, and are deduced from the control law (1).

The F_{int} force feedback has the effect of changing the inertia apparent in the manipulator. But an interesting characteristic of the impedance control system is that it can be applied without having a force sensor. In this case the force is not explicitly controlled, but depending on the impedance values used in the design of the controller, the force exerted by the system on the environment is limited.

As mentioned previously, these position/force control systems have certain special characteristics when there is a user wearing the orthosis and modulating the resulting behaviour in the interaction with the environment. The different techniques applied in this research (motion capture system, VR, AR, etc.) help to evaluate the behaviour and to optimise these control systems in the case of orthoses.

III. REAL TIME VIDEO BASED MOTION CAPTURE

Video-based motion capture consists of applying computer vision techniques, in order to recognise and obtain both the position and the orientation of the objects or people reflected in the images. This problem, which may at first seem simple, has high computation cost and in certain cases remains unsolvable. In order to help resolve
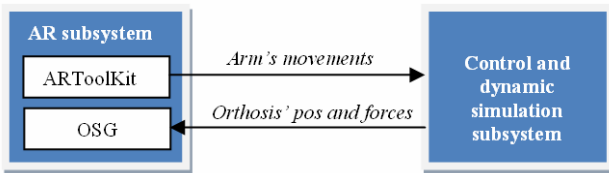
Fig. 4. Subsystems of the "BIOMIMO Design & Test".

Fig. 5. Augmented Reality subsystem.

it, markers are often used, which tend to be flat cards with a specific shape (square, circular, etc.) and an image printed on them. With these markers, both the shape and the image are known in advance, thus enabling the vision problem to be assessed on recognising these markers, and not any object or person, obtaining a much simpler process of recognition and calculation (position and orientation).

The main advantage of this kind of capture systems is the user's freedom of movement, as he does not have to wear wired sensors, but simply some small cards with the markers printed on them. However, this kind of systems also has significant disadvantages. Being of the optical type, their main problem is the occlusion of the markers. If the user covers the markers with his movements, the capture system cannot capture them. This problem is partially solved by calculating the possible position and orientation of the hidden marker by using its previous data and assuming that it will follow a similar trajectory. One commonly-used technique is the implementation of predictors using Kalman filters.

This type of capture system is perfect for use in AR systems, as it minimises the problem of registration [7] (coherence between the virtual information and the images observed).

IV. SYSTEM REQUIREMENTS TO TEST CONTROL ALGORITHMS

This study tests the performance of a virtual prototype of an orthosis with 2 DoF. In order to apply AR techniques, there are some requirements for capturing the movements of the user's arm, and some requirements for visualising the information.

A. Motion capture system requirements

The orthosis with 2 DoF only allows movements of the user's arm on its lateral plane, thus the motion capture system must be capable of capturing in real time the movements of a user's arm on this plane. To specify the arm movements, the value of the shoulder's elevation angle and the elbow angle are required for the 2 DoF orthosis. In this case it has been assumed that the user is always in an upright position with the back vertical, and it will therefore not be necessary to capture any body leaning, only the arm movements.

B. Visualization system requirements

For visualization, non-immersive AR will be used. This means that no HMD (head mounted display) will be used, but the real information, together with the virtual information (virtual prototype), will be shown on the computer screen. This visualization includes virtual objects
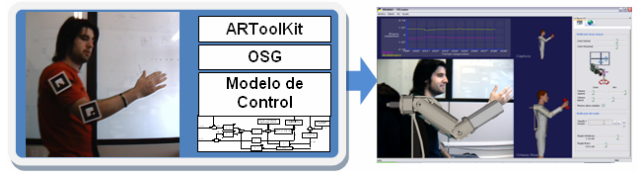
with which the user can interact: a vertical wall placed at a certain distance (parameter).

The visualization must therefore be capable of showing the video captured with the superimposed virtual model, in accordance with the information calculated by the control and dynamic simulation subsystem, all of this in real time.

V. DESIGN AND IMPLEMENTATION OF THE "BIOMIMO DESIGN & TEST" SYSTEM

The system implemented captures the position of the user's arm, and with this information, always in real time, it simulates the performance of the virtual model of the orthosis, including the model of the user's arm and the environment interacting with it (wall). Distinguishing between the hardware part and the software part, this last one can be divided into two main parts: an augmented reality subsystem and a control and dynamic simulation subsystem.

A. System overview

The functioning of the overall system is as indicated in Figure 4. Firstly, the AR subsystem captures the position of the user's arm, using the *ARToolKit* library, and sends it to the control and dynamic simulation subsystem. Secondly, the control and dynamic simulation subsystem calculates the movements of the virtual prototype of the orthosis, according to the control algorithm used and the environment considered (with or without a wall), and sends them back to the AR subsystem. Lastly, the AR subsystem is responsible for adding the image of the virtual prototype, with the movements received, onto the image of the user, using the high level *OpenSceneGraph* (*OSG*) graphics library. In addition, the movement of the user is shown (generation of movement set-point values). Throughout the whole process graphs are shown with all the position and force values, which are also saved in text files for their subsequent analysis in any statistic calculation tool.

B. Augmented Reality subsystem

The AR subsystem is divided into two parts: motion capture and visualization. The motion has been implemented using *ARToolKit* library. For the visualization the same library offers 3D drawing capacity, but they are very basic, simply enabling the designer to draw by using *OpenGL* (a low level graphics library) or *VRML* (a high level graphics library). It has therefore been considered that the *OSG* high level drawing library offers greater capacity, mainly due to the fact that it is based on the use of a scene graph. Consequently, the visualisation part has been developed by using this library.
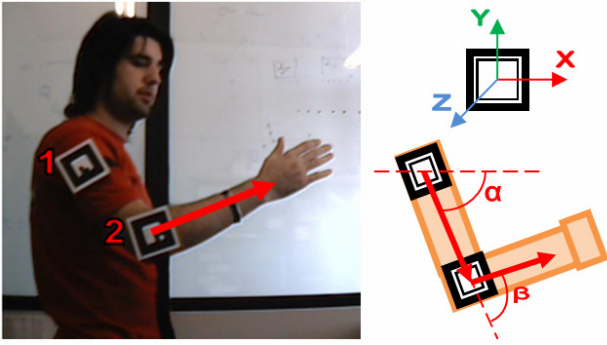
Fig. 6. Capture markers and angles calculation.

Fig. 7. Visualization screen.

The motion capture system used is of the video-based optical type. For this purpose, *ARToolKit* meets the requirements stipulated for this study. *ARToolKit* works by detecting and capturing both the position and the orientation of flat square markers. These markers always adopt the form of a black square, on a white background, with an identifying image inside. Two markers are placed on the user's arm to capture the information from it.

As shown in Figure 6, the first is placed on the shoulder and the second on the elbow, always so that they are facing the camera, to avoid the problem of occlusion. In this case, it is assumed that the user is always in an upright position and the camera is observing him from the right-hand side. The elevation angle of the shoulder will be given by the vector which goes from marker 1 to marker 2. The angle of the elbow will be given by the orientation of the elbow marker, with respect to the previous vector.

For the visualization, a programme based on MFC on Windows has been developed, in which 5 views have been included using *OSG*, as well as some view configuration dialogues. The size of each of the views and the communication ports can be configured.

In the first of the views (Figure 7), the view of the virtual prototype on the real user (with or without wall) is shown, following the movements calculated by the control subsystem. In the two right-hand views (Figure 7) a virtual human is shown with the orthosis, in one of these moving in accordance with the set-point values generated by the capture system, and in the second with the values calculated by the control and dynamic simulation subsystem, according to the interaction environment and the chosen position/force control algorithm. These two views enable the user to visually compare the performance of the control algorithm as with this system the user cannot obtain feedback from the force exerted with the environment. Finally, in the fourth and fifth views, graphs of the positions and of the force with the environment for the last 10 seconds are shown.

Although *OSG* has no software for AR applications, there are some approaches, such as the *OSGART* library, which combine the *ARToolKit*'s AR capacity with the visualisation power of *OSG*. In the case in question, a new *OSG* node, *JesAROSGTexture*, has been created, which is responsible for showing the images captured by *ARToolKit* in a texture. This node is simply included in the *OSG* scene graph and is always painted in the background of the
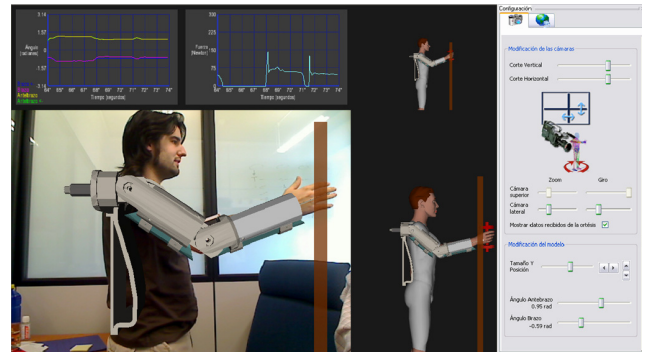
application. Finally, to make the virtual information (orthosis model) coincide with the real image (user), the *OSG* camera is configured so that it coincides with the camera values captured by *ARToolKit*. In this way, the problem of registration between the virtual information and the real information is reduced, as the system is ultimately drawing on the same image from which the calculations have been obtained.

C. Control and dynamic simulation subsystem

The control and dynamic simulation subsystem is responsible for generating the information on the virtual prototype based on the information captured. One of the main objectives of the study has been to test different position/force control algorithms. To this end, the simulation models have been created by using the *Simulink* tool, including the model of the orthosis, of the user's arm and of the contact environment (wall), in addition to the control algorithms explained earlier. The code has been obtained using *RTW* of The Math Works and loaded onto an *xPCTarget* compatible PC/104 platform, carrying out all the simulation in real time.

VI. TEST AND RESULTS

In order to test the system, members of the working group, of different heights and arm lengths, were fitted with the two markers with the verbal instructions of a coordinator. To adjust the virtual model to each arm length, the coordinator scaled the model to adjust it to the arm size, with a *slider* included in the BIOMIMO interface. Once the markers had been fitted, they were asked to move their arm up and down not too quickly and freely in order to flex the elbow as and when they pleased. A screen was also placed opposite the users for them to observe the BIOMIMO programme which operated with their movements. By activating the interaction environment (wall) one could visually observe the behaviour of the orthosis, the movement and the force exerted.

The results were in general satisfactory, highlighting several aspects which are discussed. The capture process is very sensitive to the lighting in the room, performing better in places with artificial lighting.

The positioning of the markers has a great influence on the capture process. In around the 30% of the cases, the coordinator had to correct the positioning of the markers, particularly the elbow marker, as slight rotations in this
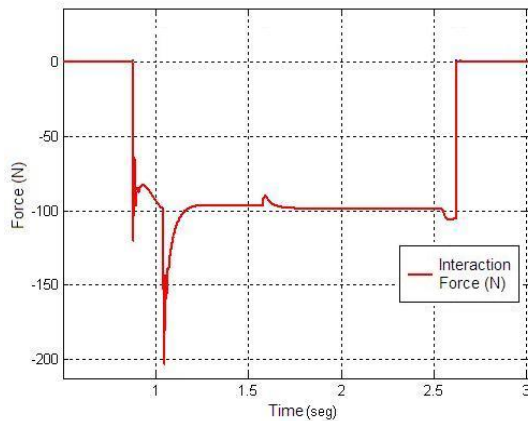
Fig. 8. Force interaction with hybrid control algorithm.

Fig. 9. Force interaction with the impedance control.

result in the angle formed by the forearm not being captured properly. The calculation of the angle of the shoulder is much more robust, as it is not based on the orientation of just one marker, but on the vector formed between the 2 markers.

Numberless than 10% of the users experienced an inconvenient latency between their movements and those reflected in BIOMIMO. The human eye can begin to perceive this sensation of latency from 40 ms, in the more sensitive users, while in this application it is operated at a medium rate of 20 frames per second (with a camera resolution of 640x480 pixels), involving a minimum latency of 50 ms. This is largely due to the capture frequency obtained from the *ARToolKit* library, the bottleneck in this application. With lower camera resolutions the capture frequency is increased and the latency would be reduced.

With regard to the control algorithms, as typical examples, Figure 8 shows the force exerted by the orthosis with respect to the virtual wall with the hybrid algorithm, when the arm movement is inserted into this wall, the force set-point value being 100 N. Clearly, the movement of the virtual prototype of the orthosis is restricted by the position of the virtual wall. Figure 9 shows the force exerted in the same case with the impedance control algorithm, where the force is not explicitly controlled, but depends on how far the arm (position set-point value) is inserted into the virtual wall.

VII. CONCLUSIONS

In general the research has achieved the established objectives. The performance of a 2 DoF virtual orthosis prototype has been proved, and two different position/force control algorithms have been tested using AR techniques.

From the interaction perspective, the motion capture system has worked correctly in this case where the movement is limited to the up and down movement of the arm, including elbow flexing. From the tests with the users, it has been concluded that the capture of the angle would be more robust and reliable by adding a marker to the hand. In this way the angle of the elbow would no longer
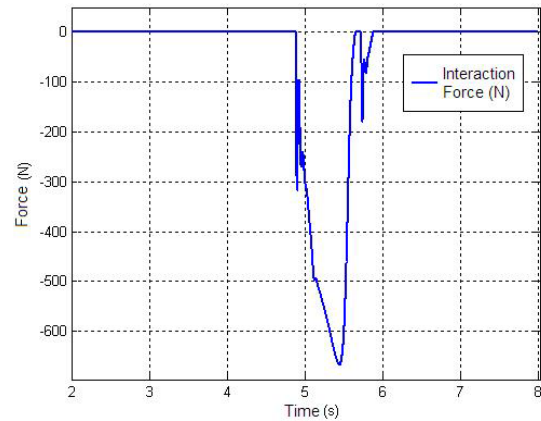
be calculated as the orientation of just one marker, but the vector formed by the elbow and hand markers would be used. It is also observed that in situations involving more complex movements, such as free movements of the arm with the 5 DoF orthosis, it would be necessary to use more cameras and more markers, in order to prevent these from being occluded and for greater robustness in the capture process.

As future work, the two main lines would be to improve the capture process, also thinking in terms of a video-based optical capture without markers; and to improve the visualization, by using an HMD (head mounted display) to perform immersive visualisation to enable the user to observe the virtual model without the need to see it on a screen, but by observing their own arm as would be the case with the real prototype.

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